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# Type Ia Supernovae Rates and Galaxy Clustering from the CFHT Supernova Legacy Survey

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## ABSTRACT

The Canada-France-Hawaii Telescope Supernova Legacy Survey (SNLS) has created a large homogeneous database of intermediate redshift ( $0.2 < z < 1.0$ ) type Ia supernovae (SNe Ia). The SNLS team has shown that correlations exist between SN Ia rates, properties, and host galaxy star formation rates. The SNLS SNIa database has now been combined with a photometric redshift galaxy catalog and an optical galaxy cluster catalog to investigate the possible influence of galaxy clustering on the SN Ia rate, over and above the expected effect due to the dependence of SFR on clustering through the morphology-density relation.

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We identify three cluster SNe Ia, plus three additional possible cluster SNe Ia, and find the SN Ia rate per unit mass in clusters at intermediate redshifts is consistent with the rate per unit mass in field early-type galaxies and the SN Ia cluster rate from low redshift cluster targeted surveys. We also find the number of SNe Ia in cluster environments to be within a factor of two of expectations from the two component SN Ia rate model.

*Subject headings:* supernovae:general — galaxies:clusters:general

## 1. INTRODUCTION

The importance of understanding Type Ia supernovae (SNe Ia) has risen greatly in recent years because of their pivotal role in demonstrating the accelerated expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999; Astier et al. 2006; Wood-Vasey et al. 2007). SNe Ia are generally agreed to be carbon-oxygen white dwarfs which have accreted sufficient mass from their companion star to initiate a thermonuclear explosion. Despite this consensus, several models exist for the companion type, the accretion process, the delay time between star formation and SN Ia explosion, and the explosion mechanism (Hillebrandt & Niemeyer 2000; Höflich et al. 2003). Photometric and spectroscopic observations, and explosion simulations, are making inroads towards a coherent picture of SN Ia events (Mazzali et al. 2007). Another (albeit indirect) path of investigation is studying the SN Ia rate in different stellar populations.

Compilation of the Cappellaro et al. (1999) supernova catalog with infrared data led Mannucci et al. (2005) to conclude that SN II, SN Ib/c, and SN Ia rates per unit stellar mass are directly correlated with host morphology and (B-K) colour, and to infer a correlation with host star formation activity. Based on this, Scannapieco & Bildsten (2005) expressed the SN Ia rate per unit stellar mass as the sum of a “delayed” component from old and a “prompt” component from young stellar populations. They parametrized the two components as A and B, proportional to the mass and star formation rate (SFR) of a galaxy respectively, and also found the “prompt” component to account for the discrepancy between low observed rates of cluster SNe Ia and the high cluster iron abundance (Maoz & Gal-Yam 2004). This “A+B” two component model has since been confirmed at intermediate redshifts with the large SNLS catalog (Sullivan et al. 2006a); the observations can also be matched with progenitor populations that have distributions of delay times as described by Mannucci et al. (2006) and Pritchett et al. (2007).

From the two component model, the SN Ia rate in galaxy clusters is expected to be lower

than in the field due to the morphology-density relation (Postman & Geller 1984): cluster galaxies are predominantly of early-type with little or no star formation. However, since clusters contain only a small fraction of the stellar mass of the Universe, it is conceivable that some hitherto undetected influence in such exotic environments could affect the SNIa rate. For example, the fraction of binary stars, or the rate of mass accretion onto the white dwarf, could be enhanced. The recent discovery of an enhanced nova rate in the core of elliptical galaxy M87 is evidence for the latter (Madrid et al. 2007). A second example is the detected SNIa rate enhancement in radio-loud early-type galaxies (Della Valle et al. 2005); such galaxies tend to be very luminous ellipticals in the centers of large clusters.

The Wise Observatory Optical Transient Survey (WOOTS) targeting 140 Abell clusters confirmed the SNeIa rate per unit mass in low redshift galaxy clusters to be consistent with the rate in early-type galaxies (Sharon et al. 2007). Recently, Mannucci et al. (2007) analyzed the Cappellaro et al. (1999) sample of 136 low redshift SNe ( $z < 0.04$ ) and found the SNIa rate in cluster early-type galaxies is enhanced by a factor of  $\gtrsim 3$  over field early-type galaxies. The large database of intermediate to high redshift SNeIa compiled by the Canada-France Hawaii Telescope Supernova Legacy Survey (CFHT SNLS) (Astier et al. 2006), and the publicly available photometric redshift galaxy and cluster catalogs for SNLS fields (Ilbert et al. 2006; Olsen et al. 2007) are ideal for extending these investigations to higher redshifts. As SNLS is not a cluster-targeted survey, further advantages over Sharon et al. (2007) include using a flexible parametrization of galaxy clustering in the environments of SNeIa, and determining simultaneous field SNIa rates for comparison to cluster rates.

§ 2 describes the SNIa, galaxy, and cluster catalogs used in this experiment. § 3 and § 4 present two independent approaches to statistically evaluate the effects of clustering on the SNIa rate per unit mass. § 3 uses a continuous clustering strength estimator to compare the SNIa rate per unit mass inside and outside clustered environments. § 4 identifies six SNIa in Olsen et al. (2007) galaxy clusters, considers the probability of these observations based on expectations from the two component rate model, and calculates the SNIa rate per unit mass in clusters. § 5 reviews and discusses the papers main findings.

A flat cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_{\text{Lambda}} = 0.7$ , and  $\Omega_M = 0.3$  is used.

## 2. OBSERVATIONS

Three catalogs are described here, all of which were generated from the four Deep fields of the Canada-France-Hawaii Telescope Legacy Survey: the Supernova Legacy Survey

catalog of type Ia supernovae<sup>1</sup>, the Ilbert et al. (2006) photometric redshift galaxy catalog, and the Olsen et al. (2007) optical galaxy cluster catalog.

## 2.1. The CFHT Supernova Legacy Survey Catalog

SNLS images four 1 deg<sup>2</sup> Deep fields (D1–D4) every three to four nights (when visible) in four MegaCam filters ( $g_M, r_M, i_M, z_M$ ) to a depth  $i_M \simeq 25$ . At the end of its five year program, the SNLS will have discovered  $\sim 500$  type Ia supernova with its imaging and spectroscopic programs (Howell et al. 2005), and be a valuable contributor to collaborative efforts in constraining the dark energy equation of state parameter  $w$  (Astier et al. 2006; Spergel et al. 2007). For this project we use the 343 SNe Ia spectroscopically identified prior to 2007 September 29.

## 2.2. Ilbert Photometric Redshift Galaxy Catalog

The Ilbert et al. (2006) galaxy photometric redshift catalog<sup>2</sup> covers the four SNLS Deep fields. They incorporate VIMOS VLT Deep Survey spectroscopic redshifts to calibrate the spectral energy distribution (SED) fitting routine, resulting in photometric redshifts with an accuracy of  $\sigma_{\Delta z/(1+z)} = 0.029$  for  $i_{AB} < 24$ , and a fraction of catastrophic errors of 1% at  $17.5 < i_{AB} < 21.5$ , increasing to 10% at  $23.5 < i_{AB} < 24$  (Ilbert et al. 2006). In optimizing the photo- $z$  calculation, the accuracies of the SEDs types are compromised (Ilbert, private communication), and the distribution of SED types is discontinuous. To solve this problem, we use 51 SEDs interpolated from Coleman et al. (1980) and Kinney et al. (1996) templates<sup>3</sup>, and fit them to the apparent magnitudes and photometric redshifts of the catalog galaxies. We then calculate  $K$  corrections and absolute magnitudes, and estimate galaxy stellar masses and star formation rates using fits of this library of SEDs to the models of Buzzoni et al. (2005), which we find to agree well (within a factor of 2) with those derived from PEGASE models (Sullivan et al. 2006b).

To ensure catalog purity, we restrict the catalog as recommended by Ilbert et al. (2006). For example, galaxies must be detected in  $i_M$ , the flag values are used to mask galaxies near foreground stars, the number of bands used for redshift fit must be at least 3, and

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<sup>1</sup><http://legacy.astro.utoronto.ca>

<sup>2</sup><http://terapix.iap.fr>

<sup>3</sup><http://www.astro.uvic.ca/~gwyn/cfhtls>

galaxies with a second peak in their redshift Probability Distribution Function indicate a likely catastrophic failure, thus are excluded (Ilbert et al. 2006). In addition we impose the limits  $i_M < 25$  and  $z < 1.2$ , and that the “object” parameter must be equal to zero indicating the object is a galaxy.

### 2.3. Olsen Optical Galaxy Cluster Catalog

The Olsen et al. (2007) cluster catalog derived from the Terapix data release in August 2005 (T0002) includes photometric redshifts and an optical grade (A–D). Olsen clusters are restricted to those of grade A, meaning a concentration of similarly colored galaxies is visible, resulting in 18, 17, 16, and 10 clusters in D1–4. This optical cluster catalog was chosen over those of other selection techniques as it provides consistent completeness for all four SNLS Deep field areas.

Olsen et al. (2007) find their cluster redshifts are slightly overestimated for  $z < 0.6$ , and underestimated for  $z > 0.7$ , with a standard deviation of  $\sim 0.1$  (Olsen et al. 2007). For the cluster redshift we instead use the peak of the redshift distribution from Ilbert catalog E/S0 and Sbc galaxies along the cluster’s line of sight (within 40 arcseconds). For distributions which plateau instead of peak, the plateau’s central redshift is used. To evaluate corrected cluster redshift precision we apply the same procedure to the VVDS spectroscopic redshift catalog<sup>4</sup>. For the four D1 clusters with VVDS galaxies along their line of sight, the differences between photometric and spectroscopic redshift peaks have a standard deviation of  $\sigma_{\Delta z/(1+z_{VVDS})} = 0.023$ , indicating good agreement.

### 2.4. Additional Catalog Processing

SNeIa host galaxies are identified as the closest neighbor in the Ilbert catalog - except when the offset difference between the nearest two is less than 2 arcseconds, in which case redshift is used to discriminate. 85 SNeIa have no neighbor within 5 arcseconds (maximum host offset), and cannot be used; this mainly includes SNeIa in hosts of  $i_M > 25$ , and on the masked regions covering  $\sim 20\%$  of field area. For the SNeIa with potential Ilbert catalog hosts, iterative outlier rejection is applied to the residual dispersion between host photometric

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<sup>4</sup><http://www.oamp.fr/virmos/>

and SNIa spectroscopic redshifts<sup>5</sup>. The photometric redshift accuracy when performed for all fields combined is  $\sigma_{\Delta z/(1+z_{SN})} = 0.030$  (consistent with Ilbert et al. 2007). However, if outlier rejection is applied to each Deep field separately, we find that each has a different photometric redshift uncertainty:  $\sigma_{D1} = 0.028, \sigma_{D2} = 0.024, \sigma_{D3} = 0.030, \sigma_{D4} = 0.050$ . In this way, 26 SNe Ia are rejected as outliers, dropping the total number to 232 SNe Ia.

The SNIa rate per year,  $SNR_{Ia}$ , is calculated for every galaxy based on the two component model, parametrized by  $SNR_{Ia} = A M + B \dot{M}$  where  $M$  is the stellar mass of the galaxy (in solar masses) and  $\dot{M}$  is the star formation rate (in solar masses per year). The most recent A and B values of Sullivan et al. (2006a) are used:  $A = 5.3 \pm 1.1 \times 10^{-14} \text{ SNe y}^{-1} \text{ M}_{\odot}^{-1}$  and  $B = 3.9 \pm 0.7 \times 10^{-4} \text{ SNe y}^{-1} (\text{M}_{\odot} \text{ y}^{-1})^{-1}$ . The expected SNIa rate per year for each galaxy is corrected to reproduce the total number observed in the SNIa sample (excluding SNe Ia with no identified host). This correction is performed for separate redshift ranges and Deep fields to account for incompleteness in observations; values are given in Table 1. The result is the number of SNIa expected in each galaxy over the observing period. These calculations are also repeated using the  $A$  (mass) component only.

### 3. PARAMETRIZED CLUSTER-LIKE ENVIRONMENTS

To begin we use a continuous clustering strength estimator to compare the SNIa rate per unit mass in and out of clustered environments. This parameter quantifies the significance ( $\Sigma$ ) of finding  $N_E$  neighbor galaxies the environment of a galaxy or SNIa, given number expected from the background distribution.  $\Sigma$  is calculated for a cylindrical volume environment of diameter  $D$  and redshift depth  $\pm \sigma_{\Delta z/(1+z)}(1+z)$  ( $\sigma$  from § 2.4) centered on the object, as in equation 1 where  $N_E$  is the number of galaxies in the environment,  $N_F$  is the number of galaxies within  $\pm \sigma_{\Delta z/(1+z)}(1+z)$  in the Deep field,  $A_E = \pi D^2/4$  is the aperture area, and  $A_F$  is the area of the field after allowing for the area occulted by foreground star masks (Ilbert et al. 2006). Since  $N_F$  is computed at the same redshift as the object being studied, incompleteness at high redshift is automatically compensated for.

$$\Sigma = \frac{N_E - N_F(A_E/A_F)}{\sqrt{N_F(A_E/A_F)}} \quad (1)$$

The advantage of this parametrization is that a strict cluster definition is avoided - any

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<sup>5</sup>A sigma of three and fractional convergence threshold of 0.01 was used; average number of iterations was 4

desired scale of clustering can be explored by altering the aperture diameter  $D$ . Environmental significances are calculated using a range of clustering scales (diameters  $D$  ranging from 0.1 to 1.5 Mpc) both for field galaxies ( $0.1 < z < 1.1$ ), and also for the 232 SNe Ia surviving the cuts in section 2.4. Normalized cumulative significance distributions for both field galaxies and SNe Ia are shown in Figure 1 for  $D = 0.6$  Mpc. A Kolmogorov-Smirnov test shows that the two samples are statistically indistinguishable: SN hosts appear to be drawn from the same population as field galaxies with respect to clustering in their environment.

Let us now turn to the most clustered environments, by defining a significance limit ( $\Sigma_{X\%}$ ) to isolate the top 10%, 5%, and 1% most significant galaxy environments – the high significance group (HSG). Figure 1 shows the HSG cutoffs for  $\Sigma_{10\%}$  as an example; actually the HSG is determined for each diameter  $D$  and each Deep field separately, then the HSGs for all are fields combined for a given  $D$ . We use summed Poisson probabilities to compare the number of SNe Ia in the HSG ( $N_{obs}$ ) to the number expected ( $N_{exp}$ ), which is the sum of the expected number of SNe Ia in each HSG galaxy (from § 2.4). The Poisson probability of observing  $x = N_{obs}$  given  $\mu = N_{exp}$  is expressed by equation 2 (Bevington & Robinson 2003), and the summed Poisson probabilities for  $x > \mu$  and  $x < \mu$  are given in equations 3 and 4 respectively.

$$P_P(x; \mu) = \mu^x \frac{e^{-\mu}}{x!} \quad (2)$$

$$P_{SUM}(x, \infty; \mu) = \sum_{x'=x, x+1, \dots}^{x'=\infty} P_P(x'; \mu) \quad (3)$$

$$P_{SUM}(0, x; \mu) = \sum_{x'=0, 1, \dots}^{x'=x-1} P_P(x'; \mu) \quad (4)$$

As expressed by the morphology-density relation, galaxy clusters are dominated by early-type galaxies (Postman & Geller 1984), so Poisson probabilities are also calculated for the subset of early-type field galaxies and SNe Ia hosts in the HSG. Results for a representative sample of environment diameters in Table 2 show the number of HSG SNe Ia to be consistent with expectations of the two-component model over a range of  $D$  and  $\Sigma_{X\%}$ . Thus we conclude this clustering parametrization method does *not* show an influence of clustering on SNe Ia events. Neither including the SNe Ia outliers rejected in § 2.4, nor increasing the environment redshift depth to  $\pm 2\sigma(1+z)$ , affects this conclusion.

#### 4. SNIa IN OLSEN CATALOG CLUSTERS

Here we identify SNeIa and galaxies in grade A clusters from the Olsen et al. (2007) cluster catalog. We use Poisson probabilities (§ 4.1) and a direct calculation of SNeIa rates in clusters (§ 4.2) to look for an influence of clustering on the SNIa rate per unit mass. As the SNLS detection efficiencies of Neill et al. (2006) are valid for  $0.2 < z < 0.6$ , we restrict cluster, galaxy, and SNIa redshifts to this range to use of them. This decreases the catalogs to 30 clusters, 70587 galaxies, and 109 SNeIa. We note Olsen et al. (2007) and Ilbert et al. (2006) use different Terapix data releases (T0002 and T0003 respectively), and the release used by Olsen et al. has more masked regions. However the differences in field effective areas are  $\lesssim 10\%$ , so likely only  $\lesssim 3$  clusters of Ilbert catalog galaxies are missing from the Olsen catalog.

SNeIa and galaxy members of clusters are identified as are neighbors in the environment of a galaxy in § 3, except the volume is centered on the cluster coordinates. Since the cluster filter used by Olsen et al. (2007) has a profile with core radius  $r_c = 0.133h_{75}^{-1}$  Mpc and cut off radius of  $r_{co} = 1.33h_{75}^{-1}$  Mpc, results for 0.4, 0.8, and 1.5 Mpc will be presented as representative. For galaxies a redshift depth of  $\pm 2\sqrt{(\sigma_{\Delta z/(1+z_{SN})})^2 + (\sigma_{\Delta z/(1+z_{VVD S})})^2} (1+z_C)$  is used, a convolution of uncertainties in cluster redshifts from § 2.3 and galaxy redshifts from § 2.4. As SNeIa have spectroscopic redshifts, a redshift depth of simply  $\pm 2\sigma_{\Delta z/(1+z_{VVD S})}$  is appropriate. Images in Figure 2 and data in Table 3 present 6 SNeIa identified in Olsen clusters. While the 3 SNeIa within  $D = 0.8$  Mpc are probably physically associated with the clusters, this cannot be said for the remaining three. The number of field SNeIa with  $0.2 < z_{SN} < 0.6$  predict  $\sim 1.8$  SNeIa would randomly appear in the regions between  $r = 0.4$  and  $r = 0.75$  Mpc and  $\pm 2\sigma_{\Delta z/(1+z_{VVD S})}$ . The probabilities of all 3 being random and all 3 *not* being random associates are both  $< 20\%$ . As it remains likely that at least one is physically associated with a cluster we include them in our results, but remind the reader that interloping SNeIa (and galaxies) will add to the uncertainties for  $D = 1.5$  Mpc.

##### 4.1. Summed Poisson Probabilities

Summed Poisson probabilities (defined in § 3) of observing these cluster SNeIa are computed from the number expected in the identified member galaxies, for all galaxy types and early-types only. Table 4 shows these observations are consistent with the two-component SNIa rate model. In fact,  $\geq 6$  SNeIa would have to have been observed within  $D = 0.4$  Mpc of galaxy clusters ( $\geq 8$  or 0 for  $D = 0.8$  Mpc) for  $P_{SUM} < 0.05$ . This constrains the SNIa rate in clusters to agree with the two-component model to within a factor of two.



Obviously, to detect an effect on SNeIa rates due to clustering (over and above the expectations of the two component model and morphology-density relation) lurking in this data, we should at least detect the two component model. So can we rule out the single component model (mass or “A” component only) from these cluster observations? The answer appears to be no. Table 4 shows that the number of observed cluster SN Ia is actually consistent with *both* models. Surveys to test for the A+B model or more complicated delay time distributions (Mannucci et al. 2006) will require a larger survey (two to three times the area or duration); unfortunately, the final SNLS data set will not be adequate for this.

## 4.2. SN Ia Rates in Clusters

Here we use detection efficiencies from Monte Carlo simulations of the SNLS SN Ia identification pipeline from Neill et al. (2006) to directly calculate the SN Ia rate per unit mass in clusters, and compare it to that for the field. The corrected number of SN Ia which exploded in a given field in a year,  $N_{corr,Ia}$ , is extracted from equation 3 of Neill et al. (2006). As shown in equation 5,  $N_{Ia}$  is the total number of supernova observed in a given field;  $S$  is the number of observing seasons;  $\epsilon_{yr}$  is the detection efficiency per year (the probability of a supernova being detected, sent for spectroscopy, and identified as a type Ia); and  $C_{SPEC}$  accounts for the fraction of SNeIa for which spectra are obtained yet remain unidentified.  $[1 + \langle z \rangle_V]$  corrects for time dilation at the volume-weighted average redshift of the survey, and  $\langle z \rangle_V = 0.46$ . Detection efficiencies from Neill et al. (2006) and the number of observing seasons for each field up to January 2007 are in Table 5. Approximations to Poisson uncertainty from Gehrels (1986) determine the upper and lower limits on  $N_{Ia}$  at the 0.84 confidence level (corresponding to  $1\sigma$ ), which are substituted into equation 5 to determine  $\Delta N_{corr,Ia}$ .

$$N_{corr,Ia} = \frac{N_{Ia}/S}{\epsilon_{yr}C_{SPEC}}[1 + \langle z \rangle_V] \quad (5)$$

Table 6 contains the resulting corrected SN Ia rate per unit mass per year in clusters and the field. With only 3 identified cluster SNeIa, statistical uncertainties dominate this calculation; systematics, mainly the error in galaxy mass calculations, are likely another  $\sim 30\%$ . Thus, our SN Ia rate is consistent with both the rate in early-type galaxies,  $5.3 \pm 1.1 \times 10^{-14}$  SNe  $y^{-1} M_{\odot}^{-1}$  (Sullivan et al. 2006a), and the low redshift cluster rate from WOOTS,  $9.8_{-3.9}^{+5.9} \pm 0.9 \times 10^{-14}$  SNe  $y^{-1} M_{\odot}^{-1}$  (Sharon et al. 2007).

There are two factors not considered which could affect SN Ia detection efficiencies in cluster galaxies. First, SN Ia detection efficiencies decrease in brighter hosts (Neill et al. 2006),

and the brightest galaxies are early-type. Second, the SNIa detection efficiency decreases for fainter, lower stretch SNIa, and these faint SNIa occur preferentially in early-type hosts (Sullivan et al. 2006a). Since cluster galaxies are predominantly early-type, both of these effects dominate in clusters: the first effect decreases the number expected in clusters by  $\sim 15\%$ , but quantifying the second would require more detailed completeness simulations. Both effects would cause us to underestimate the rate of SNeIa in clusters relative to the field.

### 4.3. SNIa Rates in E/S0 Cluster Galaxies

To avoid these effects and the morphology-density relation, we limit the galaxy sample to two subsets: all early-type galaxies, and the brightest population of early-type galaxies (those with  $M_V < -23.0$  like brightest cluster galaxies, BCGs). This has the added benefit of rejecting interlopers misidentified as cluster members. Two cluster SNeIa have early-type hosts, and the host of 03D1ax is brighter than  $M_V = -23.0$ . Detection efficiency corrections are performed as described above, with the final results and rates presented in Table 6.

Although these samples are more sensitive to the two detection efficiency biases affecting early-type galaxies (§ 4.2), limiting all galaxies to early-types minimizes differences between the clusters and the field and results in a more meaningful test. The results, although not statistically significant, are *suggestive* of the rate enhancement in cluster over field early-type galaxies established by Mannucci et al. (2007). An enhancement in BCG-like galaxies would be consistent with the findings of an enhanced SNIa rate in radio loud elliptical galaxies (Della Valle et al. 2005), as these are usually the brightest cluster galaxies. Future work will investigate the rates of SNLS SNeIa in radio galaxies using existing radio catalogs for the Deep fields.

### 4.4. Effects of Altering Data Constraints

Including grade B clusters from the Olsen et al. (2006) catalog increases the total number of clusters to 65, with one new cluster SNIa identified (03D1fb at  $z_{SN} = 0.498$  in an E/S0 host of  $M_V = -21.9$  with cluster offset  $57.8''$ ). This does not affect the conclusions of the Poisson probability experiment (§ 4.1). The resulting cluster rates for  $D = 0.8$  Mpc for all galaxy types, early-types, and the brightest early-types only are  $6.7^{+8.5}_{-3.0}$ ,  $6.7^{+11.0}_{-3.4}$ , and  $6.2^{+29.2}_{-5.1} \times 10^{-14}$  SNe  $y^{-1} M_{\odot}^{-1}$ ; slightly below yet well within uncertainties of results with A grade clusters only.

None of the SNe Ia rejected as outliers in § 2.4 are associated with Olsen catalog clusters. Including them does not affect the conclusions of the Poisson probability experiment, and only increases the SNe Ia field rate for all galaxy types to  $15.9^{+1.8}_{-1.5} \times 10^{-14}$  SNe  $\text{y}^{-1} \text{M}_{\odot}^{-1}$ . Including in the experiment all SNe Ia for which no host was identified does not yield any new cluster SNe Ia either.

Reducing the SNe Ia sample to those included in Neill et al. (2007) avoids a possible over-correction for detection efficiencies which might arise from extending the sample to later times, if the survey became more efficient (we estimate any improvement in detection efficiency to be small). This decreases the number of SNe Ia to 40, with one cluster SNe Ia (03D1ax). This does not alter the overall conclusions of these experiments.

Lastly, the inclusion of SNLS SNe Ia candidates which did not receive spectroscopic confirmation (past maximum light, or detected as field season was ending), but which were given photometric types and redshifts using the techniques of Sullivan et al. (2006b), does not yield any new cluster SNe Ia or affect the conclusions of these experiments.

## 5. CONCLUSIONS

Type Ia supernova, galaxy, and cluster catalogs generated from the first four years of CFHTLS Deep survey data were combined to search for an influence of clustering on the SNIa rate per unit mass. To avoid cluster-specific detection efficiencies and the inclusion of interloping galaxies as cluster members, we also considered subsets of regular and BCG-like early-type galaxies only. Results are dominated by the statistical uncertainties in identifying only three probable and three possible cluster SNe Ia, and consistent with the results of low redshift cluster SNe Ia rate studies. To capitalize on SNLS’s inclusion of both field and cluster environments, we used the continuous clustering strength parameter “significance” to compare the SNIa rate per unit mass in and out of clustered environments, but did not find evidence of a clustering influence on the SNIa rate per unit mass. Future work includes incorporating existing radio and infrared catalogs to investigate the rates of SNLS SNe Ia in radio loud and infrared luminous galaxies, and the VIRMOS spectroscopic redshifts for Deep field galaxies to explore the SNe Ia rate in small groups.

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*Facilities:* CFHT.

## REFERENCES

- Astier, P. et al. 2006, A&A, 447, 31
- Bevington, P. & Robinson, R. 2003, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw-Hill Companies Inc.)
- Buzzoni, A. 2005, MNRAS, 361, 725
- Cappellaro, E., Evans, R., Turatto, M. 1999, A&A, 351, 459
- Coleman, G.D., Wu, C.C. & Weedman, D.W. 1980, ApJS, 43, 393
- Della Valle, M., Panagia, N., Padovani, P., Cappellaro, E., Mannucci, F., & Turatto, M. 2005, ApJ, 629, 750
- Gehrels, N. 1986, ApJ, 303, 336
- Hillebrandt, W. & Niemeyer, J.C. 2000, ARA&A, 38, 191
- Höflich, P., Gerardy, C., & Linder, E. 2003, LNP, 635, 203
- Howell, D.A. et al. 2005, ApJ, 634, 1190
- Ilbert, O. et al. 2006, A&A, 457, 841

- Kinney, A.L., Calzetti, D., Bohlin, R.C., McQuade, K., Storchi-Bergmann, T., & Schmitt, H.R. 1996, *ApJ*, 467, 38
- Madrid, J.P., Sparks, W.B., Ferguson, H.C., Livio, M., & Macchetto, D. 2007, *ApJ*, 654L, 41
- Mannucci, F., Della Valle, M., Panagia, N., Cappellaro, E., Cresci, G., Maiolino, R., Petrosian, A., & Turatto, M. 2005, *A&A*, 433, 807
- Mannucci, F., Della Valle, M., Panagia, N. *MNRAS*, 370, 733
- Mannucci, F., Maoz, D., Sharon, K., Botticella, M.T., Della Valle, M., Gal-Yam, A. & Panagia, N., 2007, *MNRAS*, in press, (astro-ph/0710.1094)
- Maoz, D. & Gal-Yam, A. 2004, *MNRAS*, 347, 951
- Mazzali, P.A., Röpke, F.K., Benetti, S., & Hillebrandt, W. 2007, *Science*, 315, 825
- Neill, J.D. et al. 2006, *AJ*, 132, 1126
- Olsen, L.F. et al. 2007, *A&A*, 461, 810
- Perlmutter, S. et al. 1999, *ApJ*, 517, 565
- Postman, M. & Geller, M.J. 1984, *ApJ*, 281, 95
- Pritchett, C.J., Howell, D.A., & Sullivan, M. 2007, *Nature*, submitted
- Riess, A. et al. 1998, *AJ*, 116, 1009
- Sharon, K., Gal-Yam, A., Maoz, D., Filippenko, A.V., & Guhathakurta, P. 2007, *ApJ*, 660, 1165
- Scannapieco, E. & Bildsten, L. 2005, *ApJ*, 629, L85
- Spergel, D.N. et al. 2007, *ApJS*, 170, 377
- Sullivan, M. et al. 2006, *ApJ*, 648, 868
- Sullivan, M. et al. 2006b, *AJ*, 131, 960
- Wood-Vasey, M. et al. 2007, *ApJ*, 666, 694

Table 1: SN Ia rate correction factors.

Redshift Range	D1	D2	D3	D4
0.0-0.5	1.431	1.016	1.538	0.896
0.5-0.7	1.203	0.511	0.940	0.999
0.7-0.9	0.523	0.194	0.418	0.616
0.9-1.1	0.078	0.065	0.140	0.118
1.1-1.3	0.000	0.000	0.000	0.000

Table 2: Results of the clustering parametrization method for D1–4.

Diameter (Mpc)	$\Sigma_{10\%}$			$\Sigma_{5\%}$			$\Sigma_{1\%}$		
	$N_{obs}$	$N_{exp}$	$P_{SUM}$	$N_{obs}$	$N_{exp}$	$P_{SUM}$	$N_{obs}$	$N_{exp}$	$P_{SUM}$
0.4	21	26.9	0.15	11	15.0	0.18	3	3.98	0.44
0.6	27	26.5	0.48	16	14.7	0.41	5	3.41	0.26
0.8	21	25.3	0.23	12	13.8	0.38	5	3.15	0.21
1.0	23	24.8	0.41	10	13.2	0.23	6	3.13	0.10
1.5	21	22.3	0.44	11	12.0	0.46	2	2.98	0.43
For early-type galaxies and SN Ia hosts only:									
0.4	5	7.43	0.25	3	3.77	0.48	0	0.72	0.49
0.6	6	6.86	0.47	3	3.27	0.59	0	0.60	0.55
0.8	5	6.33	0.39	3	3.08	0.63	1	0.49	0.39
1.0	3	5.98	0.15	3	2.86	0.54	1	0.59	0.45
1.5	2	5.72	0.08	2	2.76	0.48	0	0.61	0.54

Table 3: Cluster SNe Ia details.

SN Ia SNLS ID	SN Ia RA	SN Ia Dec.	SN Ia $z_{spec}$	SN Ia stretch	host type	host $M_V$	host offset	cluster $z_{phot}$	cluster offset
03D1ax	02 <sup>h</sup> 24 <sup>m</sup> 23 <sup>s</sup> .32	−04°43′14″.41	0.496	...	ES/0	-23.64	1.97″	0.53	10.8″
06D1kg	02 <sup>h</sup> 24 <sup>m</sup> 32 <sup>s</sup> .57	−04°15′02″.0	0.323	1.21	Sbc	-20.31	1.69″	0.30	47.2″
05D1by	02 <sup>h</sup> 24 <sup>m</sup> 35 <sup>s</sup> .45	−04°12′04″.2	0.299	0.99	Sbc	-21.17	0.86″	0.30	138.6″
04D1pg	02 <sup>h</sup> 27 <sup>m</sup> 04 <sup>s</sup> .16	−04°10′31″.4	0.515	1.05	Sbc	-19.62	0.18″	0.51	85.2″
05D3mq	14 <sup>h</sup> 19 <sup>m</sup> 00 <sup>s</sup> .40	+52°23′06″.81	0.246	0.90	ES/0	-21.85	4.94″	0.25	9.99″
07D3af	14 <sup>h</sup> 19 <sup>m</sup> 05 <sup>s</sup> .01	+53°06′08″.98	0.356	0.98	Scd	-18.61	0.35″	0.30	128.7″



Table 4: Summed Poisson probabilities for cluster SNe Ia for D1–4.

Cluster	A+B Components			A Component	
Diameter	$N_{obs}$	$N_{exp}$	$P_{SUM}$	$N_{exp}$	$P_{SUM}$
0.4	2	2.38	0.57	3.21	0.38
0.8	3	3.51	0.54	4.53	0.34
1.5	6	5.97	0.55	7.30	0.41
For early-type galaxies only:					
0.4	2	1.97	0.59	2.79	0.47
0.8	2	2.60	0.52	3.67	0.29
1.5	2	3.69	0.29	5.23	0.11

Table 5: Parameter values for equation 5.

Field	Seasons	$\epsilon_{yr}^a$	$C_{SPEC}^a$
D1	4.0	0.3	0.94
D2	4.0	0.22	0.88
D3	4.0	0.31	0.80
D4	4.1	0.31	0.69

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<sup>a</sup>From Neill et al. (2006).

Table 6: Corrected SNe Ia rates per unit mass for D1–4.

Galaxy Set	$N_{Ia}$	$N_{corr,Ia}$ (SNe $y^{-1}$ )	Stellar Mass ( $\times 10^{14} M_{\odot}$ )	SN Ia Rate ( $\times 10^{-14}$ SNe $y^{-1} M_{\odot}^{-1}$ )
Clusters, 0.4 Mpc	2	$2.8^{+6.4}_{-1.6}$	0.33	$8.3^{+19.4}_{-4.9}$
Clusters, 0.8 Mpc	3	$4.1^{+6.7}_{-2.1}$	0.48	$8.5^{+14.0}_{-4.3}$
Clusters, 1.5 Mpc	6	$8.1^{+7.3}_{-3.1}$	0.78	$10.4^{+9.4}_{-4.0}$
Whole Field	109	$169.1^{+19.8}_{-16.3}$	11.4	$14.8^{+1.7}_{-1.4}$
For early-type galaxies only:				
Clusters, 0.4 Mpc	2	$2.8^{+6.4}_{-1.6}$	0.29	$9.6^{+22.4}_{-5.6}$
Clusters, 0.8 Mpc	2	$2.8^{+6.4}_{-1.6}$	0.38	$7.2^{+16.8}_{-4.2}$
Clusters, 1.5 Mpc	2	$2.8^{+6.4}_{-1.6}$	0.56	$5.0^{+11.6}_{-2.9}$
Whole Field	23	$35.1^{+11.0}_{-7.2}$	6.23	$5.6^{+1.8}_{-1.2}$
For the brightest early-type galaxies only:				
Clusters, 0.4 Mpc	1	$1.3^{+6.1}_{-1.1}$	0.13	$9.8^{+45.9}_{-8.1}$
Clusters, 0.8 Mpc	1	$1.3^{+6.1}_{-1.1}$	0.15	$8.7^{+40.9}_{-7.2}$
Clusters, 1.5 Mpc	1	$1.3^{+6.1}_{-1.1}$	0.19	$7.0^{+33.0}_{-5.8}$
Whole Field	2	$2.6^{+6.3}_{-1.7}$	1.02	$2.5^{+6.2}_{-1.6}$

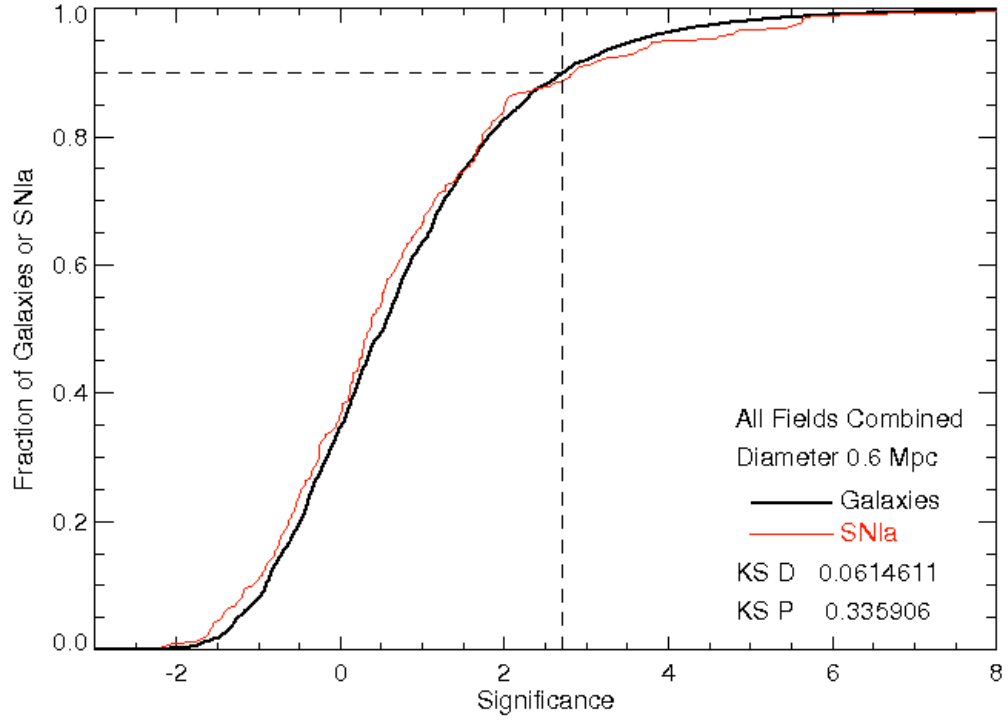


Fig. 1.— Cumulative significance distribution for galaxies and SNe Ia, with environment diameter 0.6 Mpc, for D1–4. Kolmogorov-Smirnov maximum difference (KS D) and probability (KS P) show the null hypothesis cannot be ruled out. Dashed lines represent  $\Sigma_{10\%}$ .

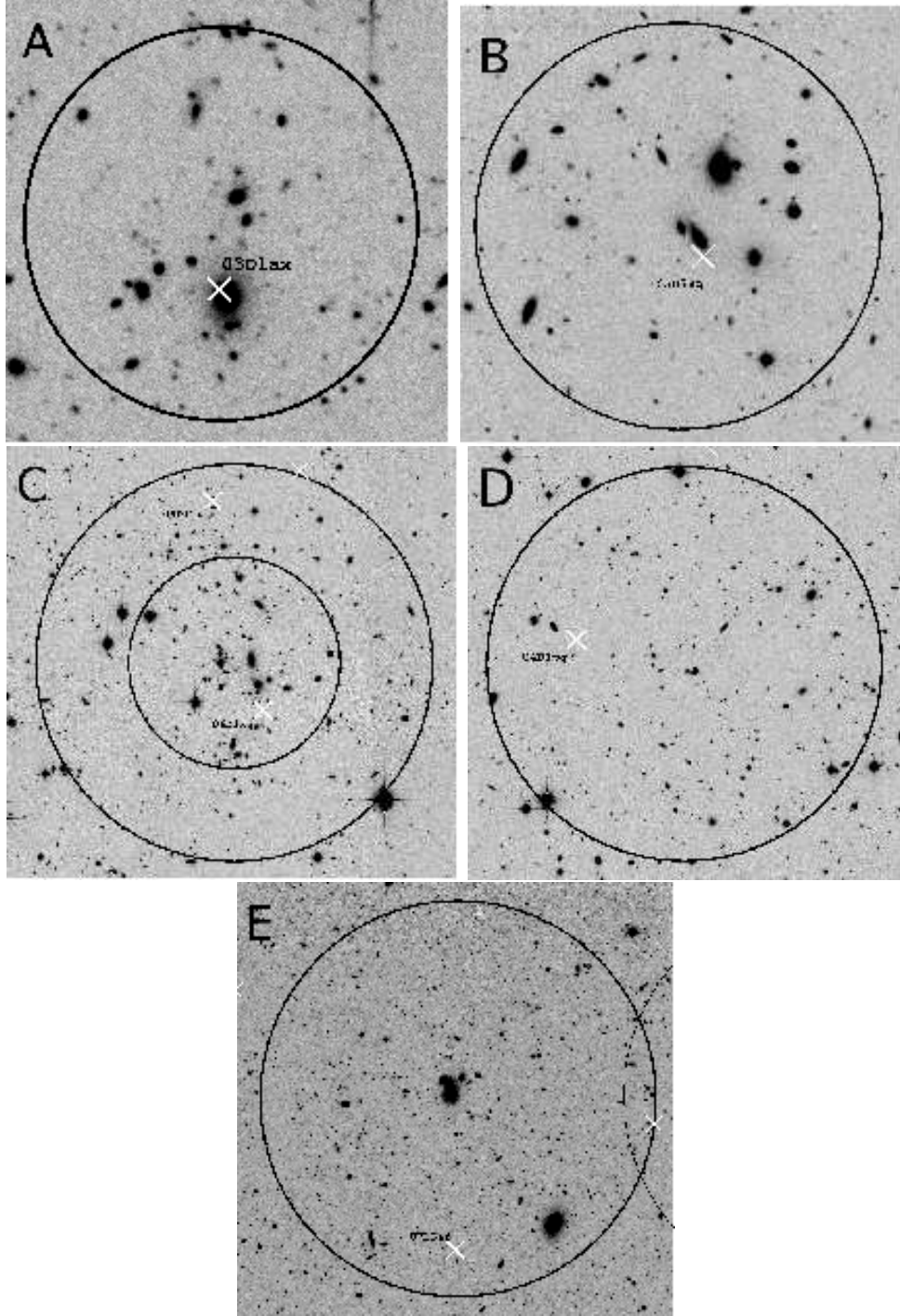


Fig. 2.— SNLS SNe Ia identified in galaxy clusters from the Olsen et al. (2007) catalog. SNe Ia coordinates marked by crosses, clusters represented by circles of diameter 0.4 Mpc (A, B), 0.8 Mpc (inner circle of C), and 1.5 Mpc (outer circle of C, D, and E). Images created from SNLS 2004 reference images and Skycat (image quality degraded for submission to astro-ph).